Structure and hydrocarbon habitat of the Polish Carpathians

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ABSTRACT

Integrated geological and geochemical studies provide an insight into the structural evolution of the Polish Carpathians and their hydrocarbon habitat and permit development of a consistent scenario for the history of their petroleum systems.

The Polish parts of the Western Carpathians are a classic fold-and-thrust belt which was largely thrusted northeastwards over the European Platform. This study centers on the Outer Carpathians and the adjacent European foreland, both of which are major petroleum provinces since a century.

The sedimentary sequence of the European Platform comprises thick Paleozoic and Mesozoic series, deposited in northwest trending grabens; these are unconformably overlain by Neogene Molasse. Although a few oil accumulations have been discovered in pre-Tertiary series, most of the gas produced in Polish Carpathians comes from the Neogene foredeep sequence.

The Outer Carpathians consist of several major tectonic units, involving Cretaceous and Paleogene flysch. These units exhibit strong lateral facies and thickness changes; these were induced by differentiation of the basin floor into cordilleras and sub-basins during successive compressional episodes, culminating in the Laramide inversion episode. During the Paleogene, flexural basin subsidence commenced. Beginning with the Late Oligocene, the basin geometry was modified by the successive emplacement of nappes, ending during Sarmatian times. These allochthonous units contain a number of accumulations which are reservoired in Cretaceous to Oligocene sands. Moreover, they contain the source-rocks for all oils discovered both in the autochthon and the allochthon. The Nosowka oil field, which may be sourced by Palaeozoic series, is an exception. The best potential source-rocks are the Early Oligocene Menilite shales which exhibit strong vertical and lateral variations in their Total Organic Content (2-15%) and Hydrocarbon Index (200-750); organic matter varies from a good type II (marine origin) in the lower part of the formation to a dominantly type III (continental origin) in its upper part. Additional potential source-rocks are the Albo-Aptian Spas and the Early Neocomian upper Cieszyn shales; however, these appear less prolific and their contribution to presently pooled oils has not yet been established.

Although present-day maturation patterns developed mainly after the nappe emplacement,

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initial source-rock maturation probably occurred during the pre-compressional stages in the southern part of the Silesian basin and the Dukla and equivalent basins, due to accumulation of thick sedimentary sequences. Integration of all data permits to postulate two episodes of migration: 1) Late Oligocene long distance migration from internal units, completed by later remigration of previously accumulated oils; this scenario may account for oil pooled in the Mesozoic platform reservoirs; 2) post-thrusting, short distance migration occurring within each basin from its deeper parts towards adjacent highs; this scenario probably accounts for oils pooled in the reservoirs of the allochthon. This two stage migration hypothesis requires testing by palinspastic basin modelling.

INTRODUCTION

Despite their complex surface geology, the Outer Carpathians were recognized as a major petroleum province already during the middle of the last century. Oil and gas fields were discovered in very distinct habitats (Encl. 1). Whereas gas fields are mainly restricted to the Neogene Carpathian foredeep, some oil fields are located in the autochthonous foreland, but most of the oil accumulations occur in the different allochthonous thrust units.

Although a common source-rock, namely the Oligocene Menilite shales, has been proposed for a long time for the oil accumulations contained both in the autochthon and allochthon (Ulmishek and Klemme, 1990), only recent geochemical analyses were able to establish a clear oil to source-rock link. This paper presents the results of integrated geological and geochemical studies and outlines the evolution of the petroleum systems of the Polish Carpathians. Particularly, the vertical and lateral distribution of the potential source-rocks, as well as oil to source-rock correlations, are compared with the present occurrence of hydrocarbons. The present and inherited maturation stages of these source-rocks are discussed in the light of present and past geometries of the fold-and-thrust belt in order to establish the timing of hydrocarbon generation episodes and to identify migration paths between kitchens and traps.

GEOLOGICAL FRAMEWORK

The area under discussion encompasses two distinct domains: 1) the Outer Carpathians, which consist of several nappes involving allochthonous Cretaceous to Paleogene terrigenous sequences, detached from their initial substratum during the Miocene thrusting phases, 2) the southern extension of the European foreland platform, which is partly overlain by Neogene synflexural sequences (essentially Miocene Molasse), deposited in the Carpathian foredeep, and which is partly overriden by the Carpathian nappes.

European Foreland

The **pre-Tertiary substratum** of the foreland is characterized by the development of a system of elongated NW-SE trending horsts and grabens, the Holy Cross Mountains, Miechow trough and Lublin basin, which were inherited from Variscan deformations and were subsequently affected by Late Permian to Jurassic rifting and Late Cretaceous to Paleocene inversion episodes (see e.g. Znosko, 1974; Ksiazkiewicz et al., 1977; Koszarski, 1985; Poprawa and Nemcok, 1988-1989; Osczypko et al., 1989). The Precambrian metamorphic and crystalline basement is overlain by Late Cambrian to Permian sedimentary formations. Among them, 1000 m of Devonian red clastics, followed by carbonates, were deposited within the Miechow trough. These are overlain by up to 400 m of Early Carboniferous carbonates and a few hundreds of metres of Namurian clastics; there is only indirect evidence for Late Carboniferous coal seams. The Precambrian to Paleozoic substratum is unconformably overlain by thick Mesozoic terrigenous and carbonate series which accumulated in grabens that were partly inverted during the Paleocene.

The **Carpathian foredeep** contains a Neogene Molasse which rests unconformably on truncated Mesozoic, Paleozoic strata or even Precambrian metamorphic rocks (Ney et al., 1974; Oszczypko and Slaczka, 1989). The Carpathian foredeep basin is narrow and relatively shallow (around 500 m) in the western part of the area, and widens and deepens (up to 2500 m) in the east (Wdowiarz, 1974). The southern parts of this basin are overriden by Outer Carpathian thrust sheets, the amplitude of which ranges from 45 km along the western cross-section (Encl. 2, section III, Roca et al., 1995) to some 70 km along the eastern cross-section (Encl. 2, section I, Roure et al., 1994). The Molasse consists mainly of fine and coarse clastic series which were deposited in a marine environment of variable salinity; its age ranges from late Burdigalian to early Tortonian (for further references see Oszczypko and Slaczka, 1989).

Outer Carpathian Units

Cretaceous and Paleogene flyschs are practically confined to the Carpathian allochthon and can be subdivided into distinct tectono-stratigraphic units, according to their structural position and lithostratigraphic composition (see e.g. Bieda et al., 1963; Kotlarczyk et al., 1985; Garlicka et al., 1989). From north to south, namely from the external to the more internal zones, the Polish Outer Carpathian flysch comprises the following units (Encls. 1 and 2, Fig. 1):

The **Stebnik unit**, which is mainly developed southeast of Przemysl in the Ukraine, is recognized to the southwest in wells Cisowa 1 and Kuzmina 1, located some 35 km south of the Carpathian thrust front (Ney et al., 1974; Ksiazkiewicz et al., 1977; Garlicka et al., 1989). This unit consists of a relatively thin, folded, mainly Miocene series, which includes lower Burdigalian evaporites and upper Badenian conglomerates; locally, it also involves uppermost Eocene and early Oligocene horizons, including the Menilite shales.

The **Borislav-Pokut unit**, which is today only exposed in the Ukraine, involves Early Cretaceous to Neogene series. In southeastern Poland, this unit is represented by small tectonic slices which outline the thrust contact between the Skole and Stebnik units south of Przemysl. The subsurface occurrence of the Borislav-Pokut unit beneath the Skole unit has been the topic of much debate (Wdowiarz and Jucha, 1981), due to its prolific hydrocarbon potential. Polish hydrocarbon exploration was initiated in this area some time before it spread to the Ukraine.

The **Skole unit**, which is restricted to the eastern part of the Polish Outer Carpathians, occupies large parts of the Ukraine. In Poland, it progressively pinches out northwestwards and disappears west of Tarnow. Where present, it consists of a thick and rather strongly deformed Early Cretaceous to early Miocene (Aquitanian or lower Burdigalian) flysch sequence. This nappe has been detached from its initial basement along Early Cretaceous black-shales.

The **Silesian unit** is present in the entire Outer Carpathians and corresponds to the major outcropping flysch nappe. It is made up of a thick sequence of latest Jurassic to Oligocene flysch series which is detached from its initial substratum along Early Cretaceous black-shales. At its northwestern front, the Sub-Silesian unit appears in tectonic slices and windows (Cieszkowski et al., 1985; Ksiazkiewicz et al., 1977). This Sub-Silesian unit is still identified southeastwards at Sanok (enl. 1) but probably disappears completely farther to the southeast. Unlike the Skole and Silesian nappes, the Sub-Silesian unit comprises only a thin sedimentary sequence, consisting of condensed Cretaceous and/or Paleogene strata which are frequently interrupted by hiatus (Ksiazkiewicz, 1960; Garlicka et al., 1989).

The **Dukla unit** represents the uppermost tectonic unit of the external Carpathian edifice of Poland. It only crops out in the eastern part of the Polish Outer Carpathians. Westwards, it is completely hiddened beneath the Magura nappe, the front of which even reaches the Silesian unit. There, its occurrence has been proved by deep boreholes and tectonic windows. Although still under discussion, the so-called Obidowa-Slopnice and Grybow sub-units could form its northwestern prolongation. The Dukla unit consists of thick,

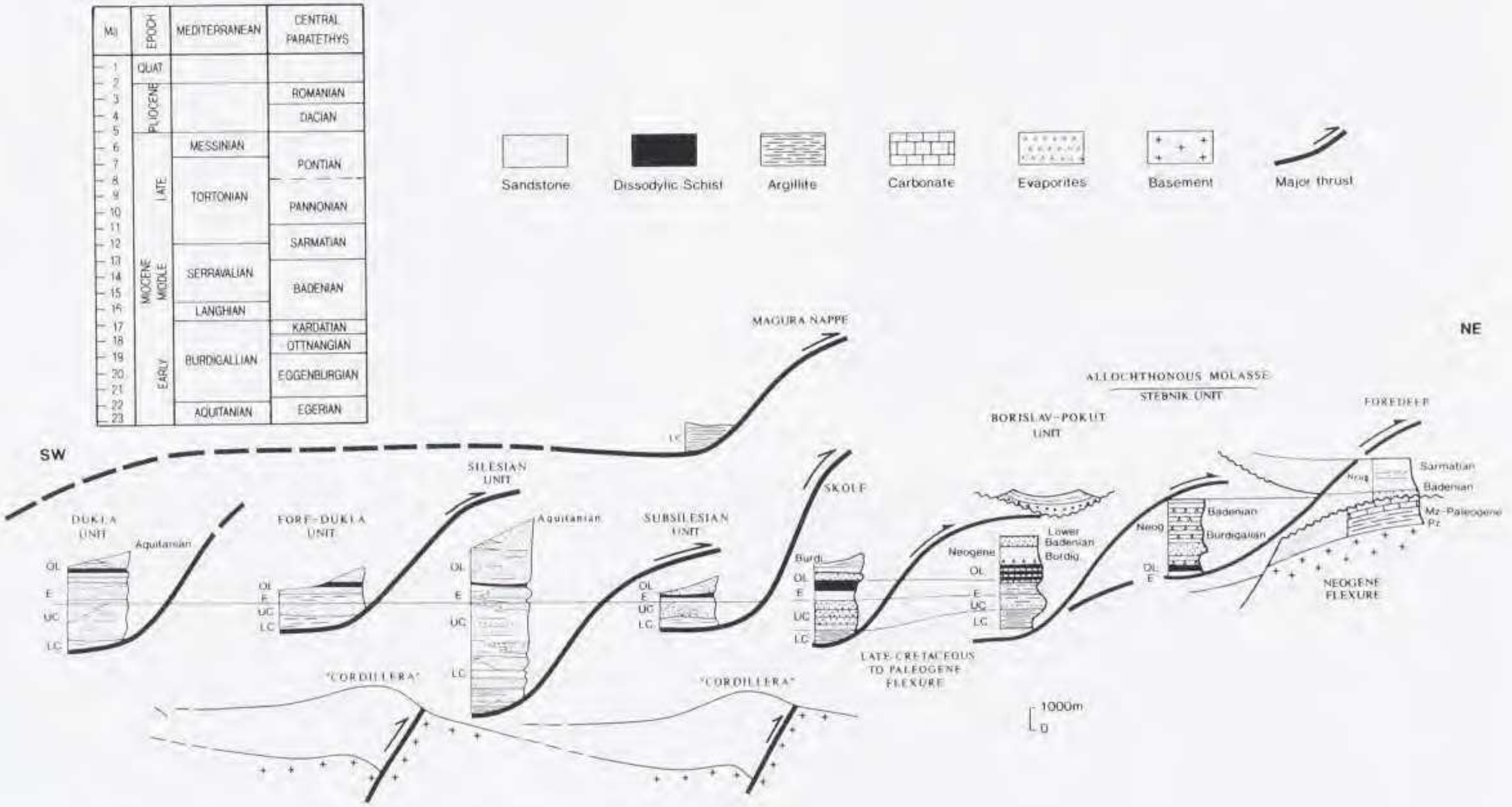

FIG. 1. Synthetic stratigraphic columns of major Outer Carpathian flysch units.

extremely deformed Cretaceous to Paleogene deep-water flysch and late Oligocene and Aquitanian Molasse sequences. In the central Polish Carpathians, the Dukla unit rests directly on top of the Silesian nappe. Elsewhere, it is separated from the latter by an additional tectonic unit, made up of Cretaceous and Paleogene condensed sequences, referred to as the "Fore-Dukla" unit in the southeast and as the "Michalczowa" unit in the west (Cieszkowski, 1992). Here, the Dukla frontal fault dips steeply beneath the south-verging backthrust structures of the Silesian unit (Ksiazkiewicz et al., 1977; Kusmierek, 1979, 1988). These units are considered as deformed paleo-highs.

The **Magura nappe**, which consists of Cretaceous to middle Miocene flysch sequences, represents the highest flysch unit of the Western Carpathians and separates the other external flysch units from the Pieniny Klippen belt (Cieszkowski, 1992; Oszczypko, 1992). It is presently restricted to the southwestern Polish Carpathians. However, isolated erosional klippen of Magura affinities are encountered further to the northeast on top of the Silesian unit, thus indicating that this nappe had previously extended further north.

The interpretation of the Sub-Silesian and Fore-Dukla units (and their equivalents) as paleo-highs or "cordilleras" (Ksiazkiewicz, 1965, 1975; Kusmierek, 1988, 1990, 1995) is based on the occurrence of repeated breaks in sedimentation and condensed sequences, but has also been inferred from paleocurrent studies, rapid thickness variations, submarine slides and turbidites on their slopes to the adjacent the basins. By applying cross-section balancing techniques and analogue modelling, the origin of these cordilleras has been related to multiple compressional phases, ranging from earliest Cretaceous up to the major Paleocene Laramide phase which induced inversion of Triassic to Jurassic extensional structures also in the Carpathian foreland (Ellouz and Roca, 1994; Roca et al., 1995).

These paleo-highs may have played a major role in the location of the décollement levels and, consequently, in the occurrence of complex and early structures (Roure et al., 1993, 1994). Early Cretaceous shales, which represent a potential décollement level, can be partly or totally eroded over these highs; this creates a discontinuity within the detachment level. In this respect, it is significant to note that major deformations, involving triangle zones or antiformal stacks of numerous duplexes, occur in areas which evolved as cordilleras during Cretaceous and Paleogene times. Examples are the Fore-Dukla (Roure et al., 1993, 1994) and the Sub-Silesian units (Roca et al., 1995). Other complex structures of the Outer Carpathians, such as the Borislav-Pokut zone in Ukraine, can also be interpreted as buried duplexes with coeval folding of the shallower units, or as triangle zones with associated backthrusts, which developed in response to the disappearance of the Early Cretaceous black-shale horizon. The Przemysl sigmoid itself is directly related to such lateral changes in décollement levels (see Encl. 1; Ellouz and Roca, 1994).

Main Stages of Mesozoic-Cenozoic Geological History

Palinspastic reconstructions of the Carpathians and adjacent areas since the Cretaceous have been attempted on the basis of balanced cross-sections (Ellouz and Roca, 1994). They show that the flysch sequences were deposited in elongated NW-SE trending basins. These basins are located in the prolongation of the NW-SE trending structures evident on the European Platform, as demonstrated at least for the external units of the Outer Carpathians. It is also evidenced that the same main tectonic events have controlled their structural and depositional history prior to emplacement of the nappes onto the foreland.

The stratigraphy (Fig. 2) and lithology of both foreland and allochthonous units have been the subject of extensive field work, reported in many papers and maps (see e.g. Ksiazkiewicz et al. 1962; Karnkowski and Oltuszyk, 1968; Sokolowski, 1976; Osika, 1980; Kotlarczyk et al., 1985; Koszarski, 1985; Poprawa and Nemcok, 1988-1989).

Following the Variscan orogeny, the Central European Platform underwent regional extension during Late Permian to Jurassic times. This led to the development of a complex pattern of intracontinental rifts and the opening of an oceanic domain in the internal Carpathians. In the European fore-

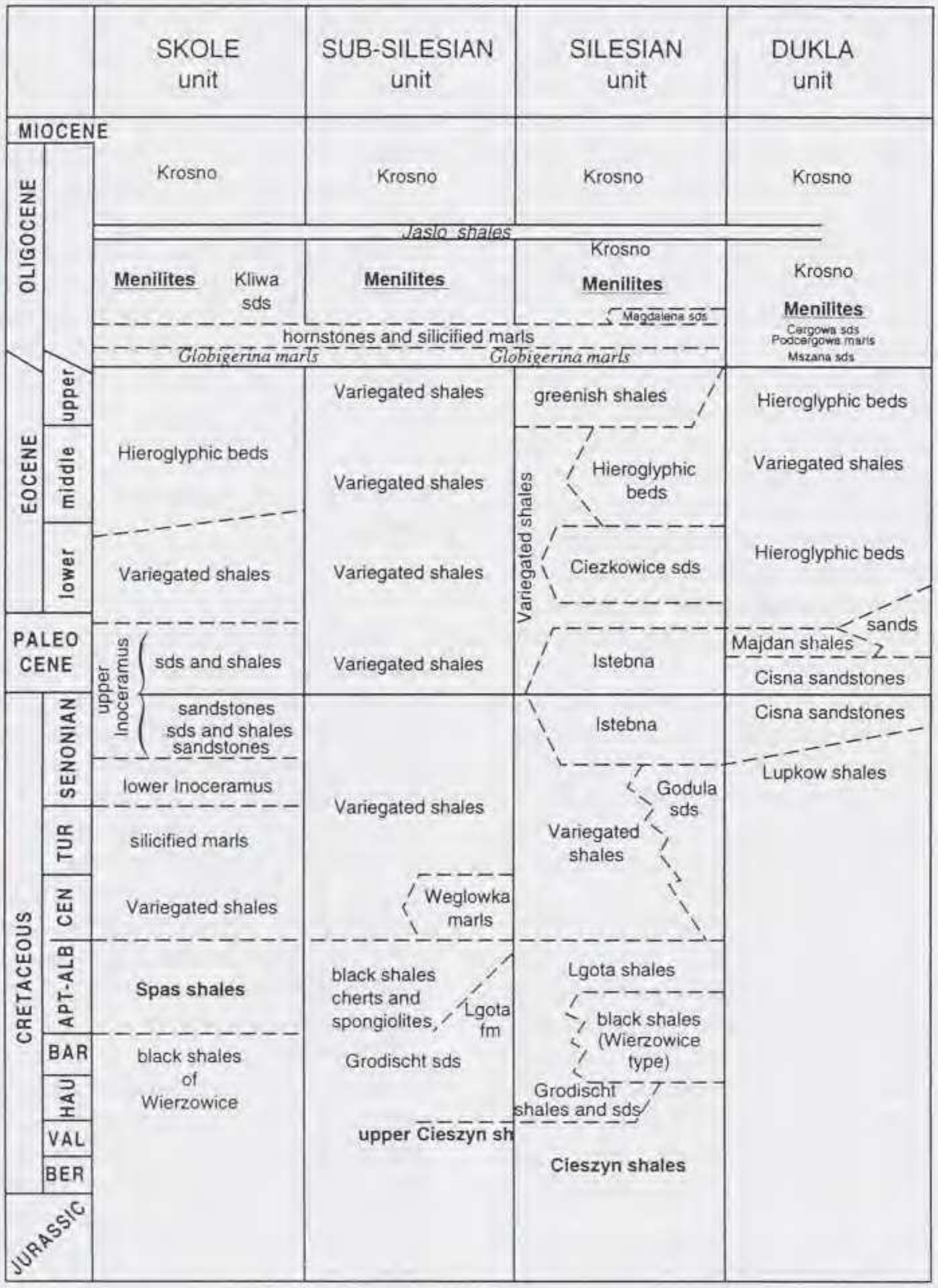

FIG. 2. Schematic stratigraphic chart of Polish Carpathians (after Gucik et al., 1962, Bieda et al., 1963).

land, major NW-SE trending structures developed during this extensional phase, including depressions and flanking highs. The now inverted Pomorze-Holy Cross Mts-Przemysl ridge corresponded to the axis of a major depression which was the site of dominantly marine sedimentation during the Jurassic and the entire Early Cretaceous. In contrast, the Miechow and Lublin basins, which flanked these troughs, were characterized by continental to shallow marine sedimentation (Koszarski, 1985; Kotlarczyk et al., 1985). At the end of Triassic, the Eo-Kimmerian phase caused uplift and erosion in the Polish Carpathian foreland. This phase has been interpreted either as compressional (Znosko, 1974; Kotlarczyk et al., 1985) or as resulting from transtensional regime (Gradinaru, 1984). During the Dogger, syn-rift tectonic subsidence led to sedimentation of clastics deposited within paleotopographical depressions in a continental and a progressively more marine environment. The overall transgression culminated during the Malm with the deposition of carbonates which reach 1500 m in thickness in the area of Tarnow-Debica. Carbonates of this age are also known from the northern margin of the Silesian and Skole basins. Southeastwards, they are unknown but are expected to be present on the basis of palinspastic considerations.

The Jurassic-Cretaceous boundary is characterized by the occurrence of tectonic movements (Late-Kimmerian phase) which can be also related to a transtensional phase. In the domain of Outer Carpathians, this phase may have initiated development of the so-called cordilleras, the presence of which is indicated by facies and current patterns since the beginning of the Early Cretaceous (Ksiazkiewicz 1960, 1965; Winkler and Slaczka, 1992). Although the entire area subsided in response to lithospheric cooling (Roca et al., 1995; Ellouz and Roca, 1994), the incipient cordilleras were repeatedly reactivated during the Cretaceous.

During the Early Cretaceous, the foreland was a dominantly continental area and underwent erosion. In the Outer Carpathians, the Early Cretaceous series is well developed in the Silesian basin (up to 800 m) and in the Skole basin (about 500 m). In the Dukla and equivalent basins, only very fragmentary data suggest that the Early Cretaceous series was deposited in a shallow to deep marine environment. It is still debated whether this basin formed part of the Silesian basin, at least during the Early Cretacous, or whether it was already well individualized. According to Ellouz and Roca (1994), the Michalczowa and the Grybow ridges, located to the north and south of the individualized Dukla basin, respectively, acted as major clastic source-arear for the Magura and Silesian basins during the Late Cretaceous.

The lowermost members of the flysch series of the Silesian and Sub-Silesian units are the Berriasian lower Cieszyn shales and limestones, and the Valanginian upper Cieszyn shales (Fig. 2). Sediments of Valanginian age, ascribed to Cieszyn formation, have also been identified in the Fore-Dukla unit (Rabe profile; Kusmierek, 1979) and could be also present in external part of the Silesian unit (Czarnorzeki profile; Kusmierek, 1985). Shaly Barremian to Albian series occur in Silesian and Skole basins (Wierzowice shales overlaid by Lgota shales in Silesian basin, Spas shales in Skole basin). Locally, these are interrupted by thick turbiditic sandstones (Grodicht in Barremian-Aptian) which were supplied from the northern margin into the Silesian and Sub-Silesian basins. At the beginning of Cenomanian, global sea-levels rose and the foreland was widely transgressed. Sands, grading upwards into marls and limestones, were deposited in the foreland while the Carpathian flysch basins were starved; in the Silesian basin, cherts and radiolarites are overlain by variegated shales, and in the Skole basin siliceous marls were deposited. However, in response to progressive uplift of the Silesian ridge, an increasing amount of sand was supplied to the southern part of the Silesian basin where it accumulated in the large deep sea-fans of the Godula formation. In the Magura and Skole basins, clastic sedimentation resumed only during the Senonian (Inoceramus formation). The clastics of the Skole basin were derived from its northern margin. In the Dukla basin, clastic deposits (Lupkow shales) are as old as early Senonian.

Whereas emplacement of the Inner Carpathian thrust-and-fold belt was completed during Turonian time, the Pieniny Klippen Belt was emplaced towards the end of the Late Cretaceous. During this Laramide phase, structures were strongly reactivated and the Polish trough in the foreland was inverted, resulting in uplift of the Pomorze-Holy Cross Mts. megaridge and concommittant isolation of Miechow and Lublin depressions. Thrust loading of the European foreland by the stacked nappes of the Inner Carpathians caused its progressive flexural subsidence and the development of the Paleogene Carpathian foreland basin. The latter was characterized by strong thickness variations, reflecting a succession of basins and cordilleras, but in a general southeastward thickening pattern. From the late Oligocene onwards, this pattern was modified by progressive emplacement of the Outer Carpathian nappes and concommittant emergence of cordilleras, supplying clastics to adjacent basins.

During the Paleocene, the Silesian cordillera continued to supply great amounts of sands to the Silesian basin (upper Istebna formation); these sands covered most of the basin and pass upwards into variegated shales. In the Skole basin, the Inoceramus sands and shales grade upwards into variegated shales, whereas in the Dukla basin, the Cisna sands are overlain by the dark Majdan shales. Clastic transport directions indicate the development of a new source-area south of the latter (Ksiazkiewicz et al., 1962). During the early Eocene, Hieroglyphic beds were deposited in Dukla basin, whereas in the Skole, Sub-Silesian basins and the outer part of the Silesian basin, variegated shales and thin-bedded flysch accumulated. At the same time, thick-bedded conglomeratic Ciezkowice sandstones were supplied to the southern part of Silesian basin. During the middle Eocene, sedimentation became more homogeneous in the Outer Carpathians due to a general decrease in tectonic activity. Regionally, the Hieroglyphic beds pass upwards into mainly pelitic, mostly shaly sediments. These are overlain by a thin horizon of Globigerina marls which was deposited over extensive areas of the Outer Carpathians. The age of this regional marker horizon is variably given as intra-late Eocene (Koszarski et al., 1974; Ksiazkiewicz et al., 1962), latest Eocene (Bieda et al., 1963; Poprawa and Nemcok, 1988-1989) or as straddling the Eocene/Oligocene boundary (Osika, 1980; Kusmierek et al., 1985).

During the Oligocene, the Menilite-Krosno formation was deposited in the Outer Carpathian domain (Fig. 2). Its basal member is made up of the sub-Menilite shales, cherts and cherty marls; in the Dukla basin, these are replaced by a dominantly sandy sediments (Mszana and Cergowa sands). The Menilite shales s.s. are dark, bituminous shales which were deposited in a pelagic or hemipelagic environment under anoxic conditions. Sands are only locally developed (Magdalena sands in the southwestern part of the Silesian basin, Kliwa sands in the Skole basin). The thickness of the Menilite shales is highly variable, ranging from 100 m in the Silesian basin to 900 m in the Dukla basin (Mruk and Kusmierek, 1991, unpubl. data). On the basis of nannofossils, where present (are often dissolved due to high organic content), an early Oligocene age is indicated for the Menilite shales (NP 21-NP 22; Muller, personal communication). These shales are overlain by the Krosno flysch, grossly dated middle-late Oligocene (NP 24-NP 25). However, the transition from Menilites to Krosno facies is gradual and diachronous, as attested by the isochronous Jaslo shale marker (Bieda et al., 1963; Jucha, 1969). Through time, the Krosno depocenter shifted progressively northeastwards from the Dukla basin (thick Krosno beds older than the Jaslo horizon) to the Skole basin (Jaslo bed at the boundary between Menilite and Krosno deposits). The Menilite-Krosno formation, as a whole, exhibits considerable thickness variations and reaches several thousands of metres in the basin centres (up to 2500 m in Dukla basin, 4000 m in Silesian basin and 1200 m in Skole basin), whereas it is absent in areas corresponding to cordilleras. During the deposition of the lower Menilite shales, these cordilleras corresponded to submerged paleohighs (no reworked material in condensed Menilite sections adjacent to these cordilleras). Later, in the middle-late Oligocene, their role as detrital sources to adjacent basins is well demonstrated (Fig. 16; Ksiazkiewicz et al., 1962; Kusmierek, 1988, 1990; Mruk and Kusmierek, 1991, unpubl. data).

In the following, we give a tentative timetable for the emplacement of the different tectonic units of the Outer Carpathians (Roure et al., 1994; Roca et al., 1995). The proposed sequence of events should not be seen as consisting of quasi-instantaneous tectonis episodes. More likely, it reflects continuous deformation during late Oligocene to mid-Sarmatian times, accounting for a large amount of supra-crustal shortening, as evident from the structural cross sections (Encl. 2). Uncertainties in this time-table arise from the erosion of the youngest deformed flysch and of the neo-autochthonous Molasse sequences (-

Ksiazkiewicz et al., 1977; Karnkowski, 1983, 1986; Oszczypko and Zytko, 1987).

The Magura nappe was mainly structured during the late Oligocene. During the early Miocene, while sedimentation of the upper Krosno formation continued in the Skole basin, the Dukla/Obidowa-Slopnice unit and the Fore-Dukla/Michalczowa unit were emplaced. The Silesian, Sub-Silesian and Skole units were mainly deformed and emplaced during the late Burdigalian and early Badenian. At this time, the present Carpathian foredeep was formed and filled with Molasse-type sediments. Its innermost parts, the Stebnik and Borislav-Pokut units, were deformed during the Sarmatian. With this, orogenic movements ended in the Outer Carpathians and the area was subjected to post-orogenic uplift and erosion.

DISTRIBUTION AND CHARACTERISTICS OF SOURCE-ROCKS

Extensive geochemical surveys were performed on the sedimentary series of the Outer Carpathians. More than 700 rock samples were collected from outcrops and cores, resulting in a high density data set for the eastern part of the Polish Outer Carpathians, whilst in their western parts sampling was more erratic (Encl. 1). In addition, few samples of the autochthonous series were collected in wells. All samples were first analyzed by Rock-Eval pyrolysis to identify potential source-rocks by their total organic carbon content (TOC), quality (HI), as well as their maturation stage (Tmax). Subsequently, additional analyses were carried out on selected samples of identified source-rocks, in order to precise their type (elemental analysis on kerogen, extract analysis, but also pyrochromatography at 550°C and preparative pyrolysis; Vandenbroucke et al., 1988). In addition, a large amount of surface samples were analyzed and dated on the basis of their nannoplankton content (Muller, personal communication).

Potential Source-Rocks In Autochthonous Series

Only very few analyses were carried out on the **pre-Cenozoic formations** of the foredeep and the nappe substratum. In the well Zagorzyce 1, a few intercalations of Early Carboniferous black-shales/silty shales were found to have a TOC around 1.5%, but a low HI around 100 mgHC/gTOC. In a well located in the Western Outer Carpathians, some Late Carboniferous coal beds show a good petroleum potential (TOC=47% and HI=450).

More than 80 samples of the **Miocene** autochthonous series were analyzed (Fig. 3; Kotarba et al., 1987). Samples from the western, central and eastern parts of Polish Carpathian foredeep are characterized by low TOC values, in the 0.5% to 0.8% range, and HI less than 120. The slight differences observed from one area to another are not significant. The Rock-Eval results and chromatograms on extracts (Kotarba et al., 1987) suggest a continental origin for this organic matter.

Potential Source-Rocks In Allochthonous Series

In the Outer Carpathian nappes, all formations were sampled and are discussed below, starting with the less organic-rich ones.

The **Late Cretaceous-Paleocene formations** (Istebna/Inoceramus formations) have very low average TOC (0.6%) and HI (<130 mgHC/gTOC). The **Eocene** Variegated shales and Hieroglyphic beds have a lower average TOC (0.3%) and a HI in the same range. In both cases, the organic matter is of probable type III (Fig. 4). It is concluded that these formations are essentially devoid of potential source-rocks. The **Late Cretaceous** Lupkow shales, which are restricted to the Dukla basin, have been sampled in only one site where they are overmature; their TOC averages 1%. One sampled site is not sufficient to make a conclusive statement about the source-rock potential of this series.

Early **Cretaceous black-shales** were sampled in different units (Fig. 7): presumably upper Cieszyn formation in Silesian unit (Stepina area)

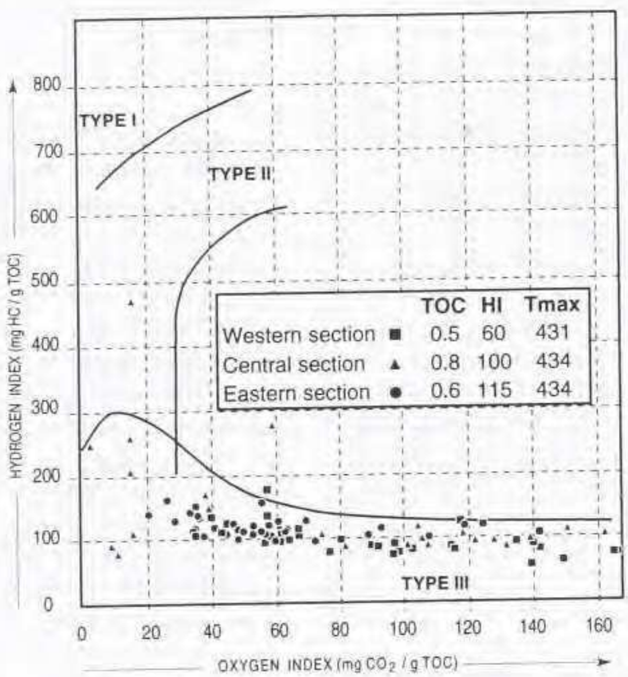

FIG. 3. Hydrogen Index-Oxygen Index diagram for Miocene formations in the Carpathian foredeep.

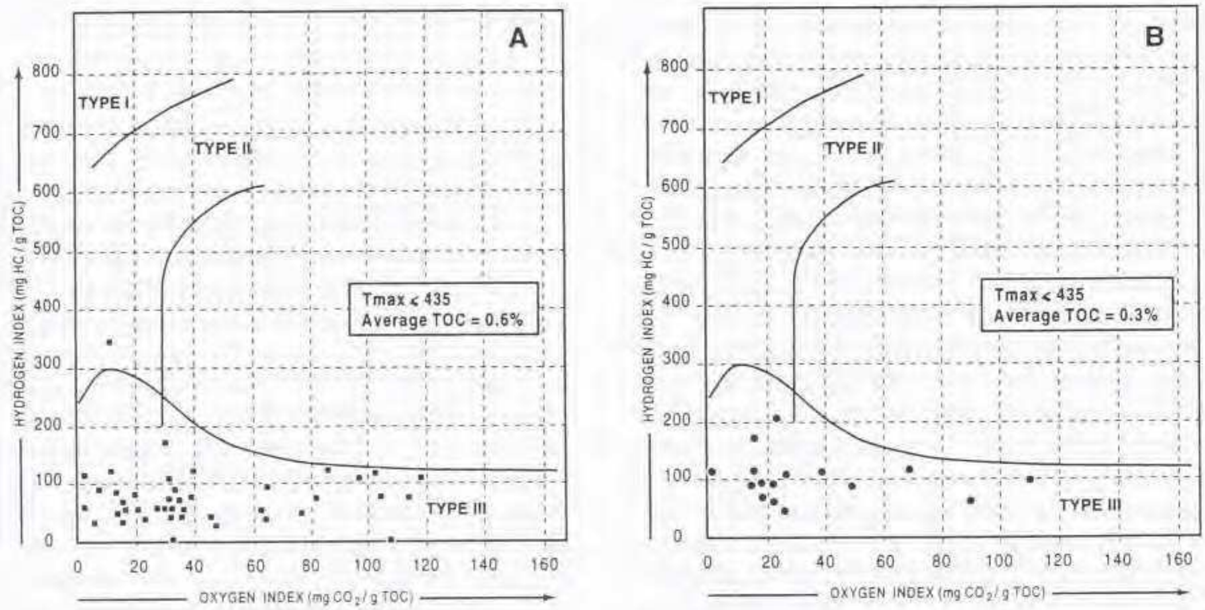

FIG. 4. Hydrogen Index-Oxygen Index diagrams: A) for Late Cretaceous-Paleocene formations (Istebna/Inoceramus formations), B) for Eocene formations (Variegated shales, Hieroglyphic beds).

and Fore-Dukla (Rabe area), Spas formation in Skole basin (Krzeczkowa area, Kuzmina 1 and 2) and the partly time-equivalent Lgota formation of the Fore-Dukla unit (Rabe area).

The **Neocomian upper Cieszyn member** can attain a thickness of 300 m and consists of alternating thin-bedded sandstones, shales and scarce siderites with locally high sand content. Berriasian to Valanginian shales sampled in the Stepina area have TOC values ranging from 1.5 to 3% (average 2%), but rather low HI of 100 mgHC/gTOC. In the Rabe area, Valanginian shales yield TOC up to 1.5 with HI of 120, despite their high maturation level (T_{max}>455) corresponding to the end of the oil-window (Espitalié et al., 1985-1986). The organic matter is of type III according to the HI-OI diagram (Fig. 6), kerogen analyses (Fig. 10) and chromatograms on extracts (Fig. 5). These shales could be considered as a potential source-rock, especially in the Rabe area. Although the facies of this formation is considered to be monotonous over wide areas (Ksiazkiewicz et al., 1962), it is questionable whether the results of limited analyses can be extrapolated to the whole area.

The **Albo-Aptian Spas formation**, is predominantly made up of black-shales which in their lower part contain sandstone intercalations. The Spas formation has a rather uniform distribution within the Skole basin. The TOC of these shales varies between 1.5% and almost 4% (average of 2%), thus expressing a vertical variability within this formation. Their average petroleum potential remains rather low : HI from 90 to 180 for a T_{max}=442°C (i.e. at the beginning of oil-window). Chromatograms on extracts (Fig. 5) and elemental analysis of kerogens (Fig. 10) clearly indicate a type III for this organic matter. Despite a rather low petroleum potential, the Spas shales can be considered as a reasonable potential source-rock. Considering the homogeneous facies development of this formation in the entire Skole basin, results of our analyses may be applicable for the whole basin.

The **Albian Lgota formation** is widely developed within the Silesian and Sub-Silesian basins and also in the Fore-Dukla zone. Dark shales are present in the middle part of this formation and alternate with thin-bedded sandstones. Their average TOC and HI are low (1% and 100 mgHC/gTOC, respectively). Accordingly, this formation has questionable source-rock characteristics. Nevertheless, the scarcity of sampling and high lateral facies variations do not allow definite conclusions on its source-rock potential.

The **early Oligocene Menilite shales** have been extensively sampled in outcrops and a few wells in the central and eastern parts of the region (Fig. 7). In contrast, in the western part, sampling was limited due to outcrop conditions and the lack of cores. The Menilite shales have been considered since a long time as a very good source-rock; our study confirms this assessment : high TOC up to 15% and high HI up to 700 mgHC/g TOC have been measured on some samples. However, our analyses point out more clearly the high vertical as well as lateral TOC (2% to 15%) variability of this formation. This is well exemplified by two stratigraphic cross sections through the Outer Carpathians (Fig. 8). A similar variability is observed in terms of quality of the organic matter with HI ranging from 200 to 750 mgHC/gTOC (Fig. 9). The wide scattering of the values observed in the OI/HI diagram is due to variations in quality of the organic matter, as all the samples but those from the Dukla unit are immature. Accordingly, the organic matter ranges from a very good type II to a type II + III.

In contrast, samples from late Oligocene Krosno formation have systematically low TOC (<1%) and low HI (<200), regardless of which area is considered. The organic matter is of type III (Fig. 9). These geochemical results are consistent with a high input of terrigenous material.

The variations in content and quality of organic matter in the Menilite formation were studied in more details at two sites in the Silesian basin-Lukawica (Fig. 11) and Rudawka-Rymanowska (Fig. 12) -and at one site on the southern margin of the Skole basin-Frysztak 3 well (Fig. 13). At these locations, the approximate thicknesses of the Menilite formation are 120, 250 and 300 m, respectively. Although sampling densities were not equal, the following general observations can be made:

(1) below the Globigerina marls, the so-called sub-Menilite shales, when present (A and possibly F1), have a middle TOC and HI (<300) and are very likely of type III.

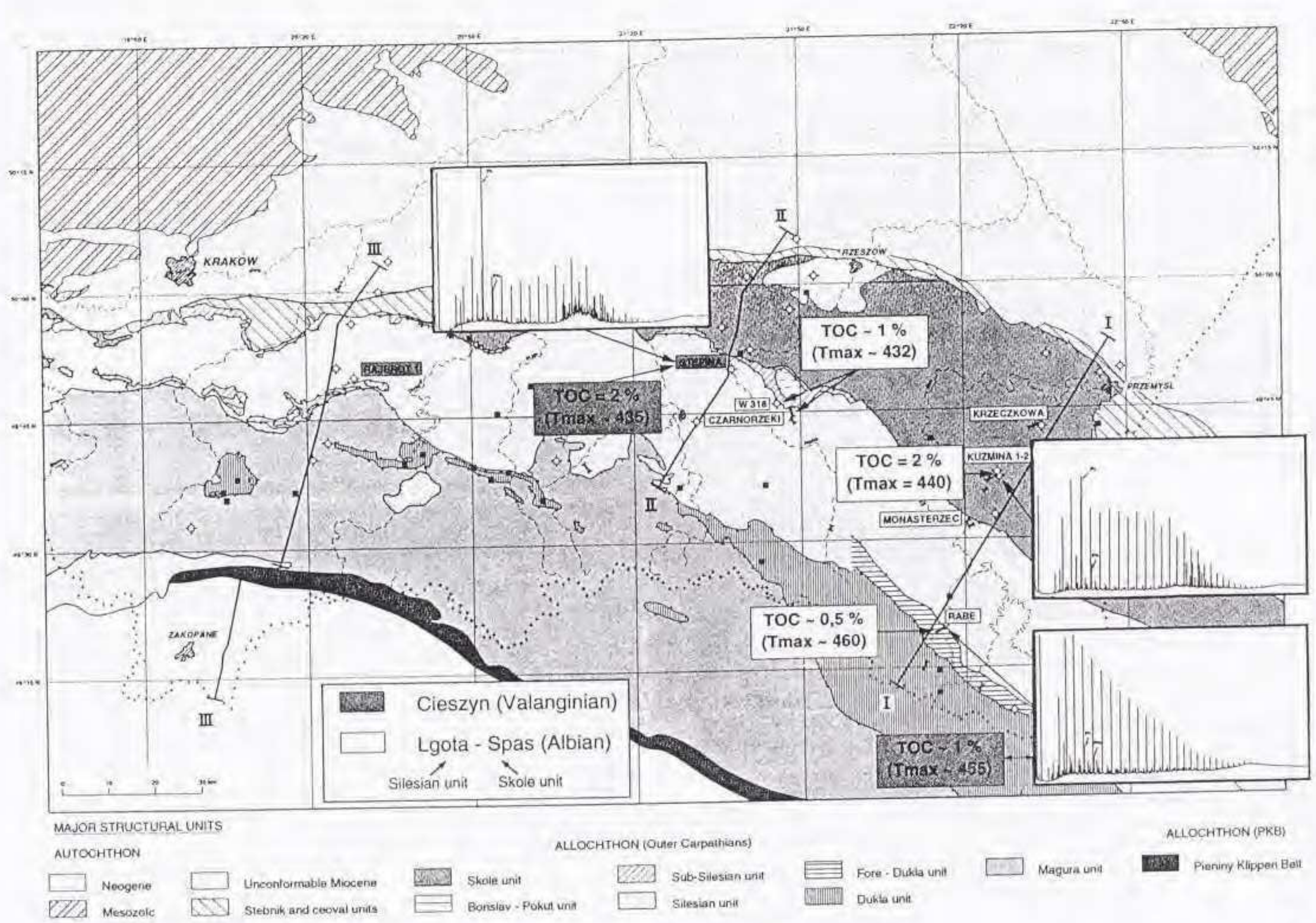

FIG. 5. Source-rock characteristics of Early Cretaceous Cieszyn and Lgota/Spas formations.

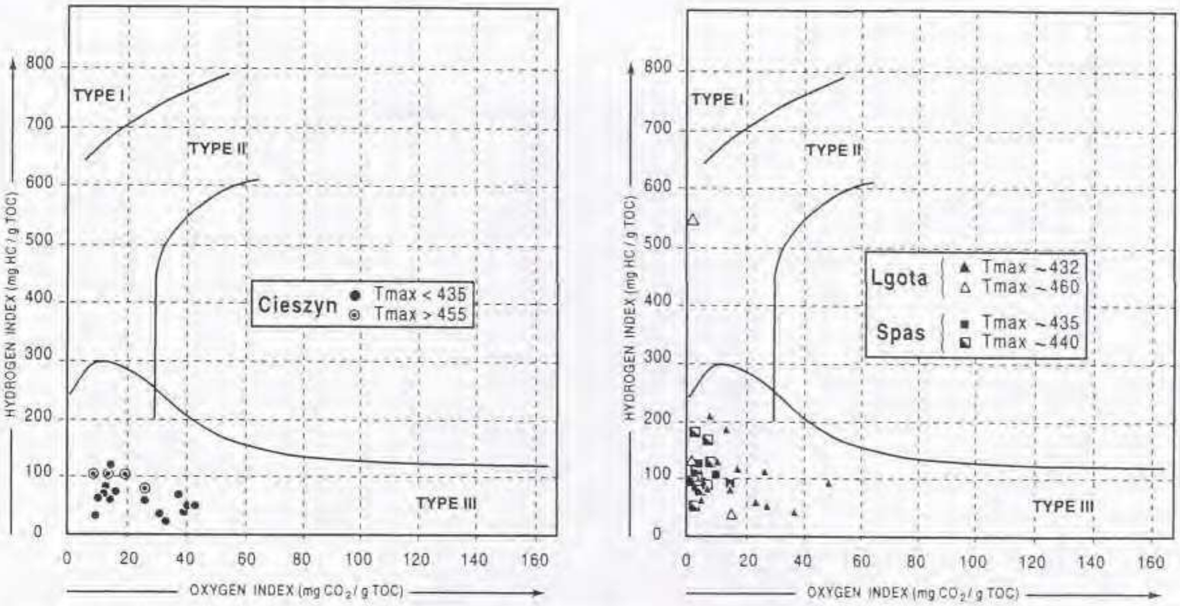

FIG. 6. Hydrogen Index-Oxygen Index diagram for Early Cretaceous formations

(2) the highest TOC and HI are consistently encountered in the lowest part of the Menilite shales, just above the Globigerina marls (samples F2, L1, L2, B). The organic matter is of very good type II as demonstrated by chromatograms and location of the kerogens in a Van Krevelen diagram (Fig. 10); its marine origin is confirmed by petrographic studies which show that it is essentially amorphous, and probably derived from marine phytoplankton. However, a very low contribution of terrestrial material (ligno-cellulosic debris) is present.

(3) higher up in the sequence, the Menilite shales exhibit a progressive decrease in TOC which corresponds to a more or less well marked decrease of the HI. This reflects primarily an increasing admixture of continental organic matter to the marine organic matter (C, D, F3, L3). Still higher in the formation (L4, F4 to F6), the terrestrial organic matter becomes predominant. This terrestrial input is marked by large amounts of saturated hydrocarbons in the C20-C30 range, a CPI>1 and a Pr/C17>>1 (the latter also confirms the low maturity level of the analysed samples).

Terrestrial input varies considerably within the Menilite formation. At the Frysztak 3 site, most of the organic matter is of continental origin. In the easternmost part of the Skole unit (Kniazyce, Gora Krepak), most of the lower Menilite series is characterized by predominantly terrestrial organic matter exhibiting low HI (<300), but alternatively high TOC (>8%) or low TOC (<3-4%) (see also Figs. 9 and 11). These results suggest at a basin scale a very heterogeneous pattern of "pure" marine versus dominantly continental organic matter within the Menilite formation and, thus, reflect a complex palaeogeographical framework during deposition of this formation.

Only few papers have been published on the depositional conditions prevailing during the accumulation of the Menilite formation in the Ukrainian Carpathians (see Koltun, 1992): development of the Menilite facies has been ascribed to the presence of an oxygen-depleted zone on the shelf and upper continental slope due to upwelling conditions, whilst the Krosno beds were deposited in deeper, more-oxygenated waters. In the Polish Carpathians, synchronous occurrence of the organic-rich (lower) Menilites, regardless of their location in the basin, speaks for a regional control on factors responsible for the accumulation of organic matter, such as a relative sea-level rise, possibly

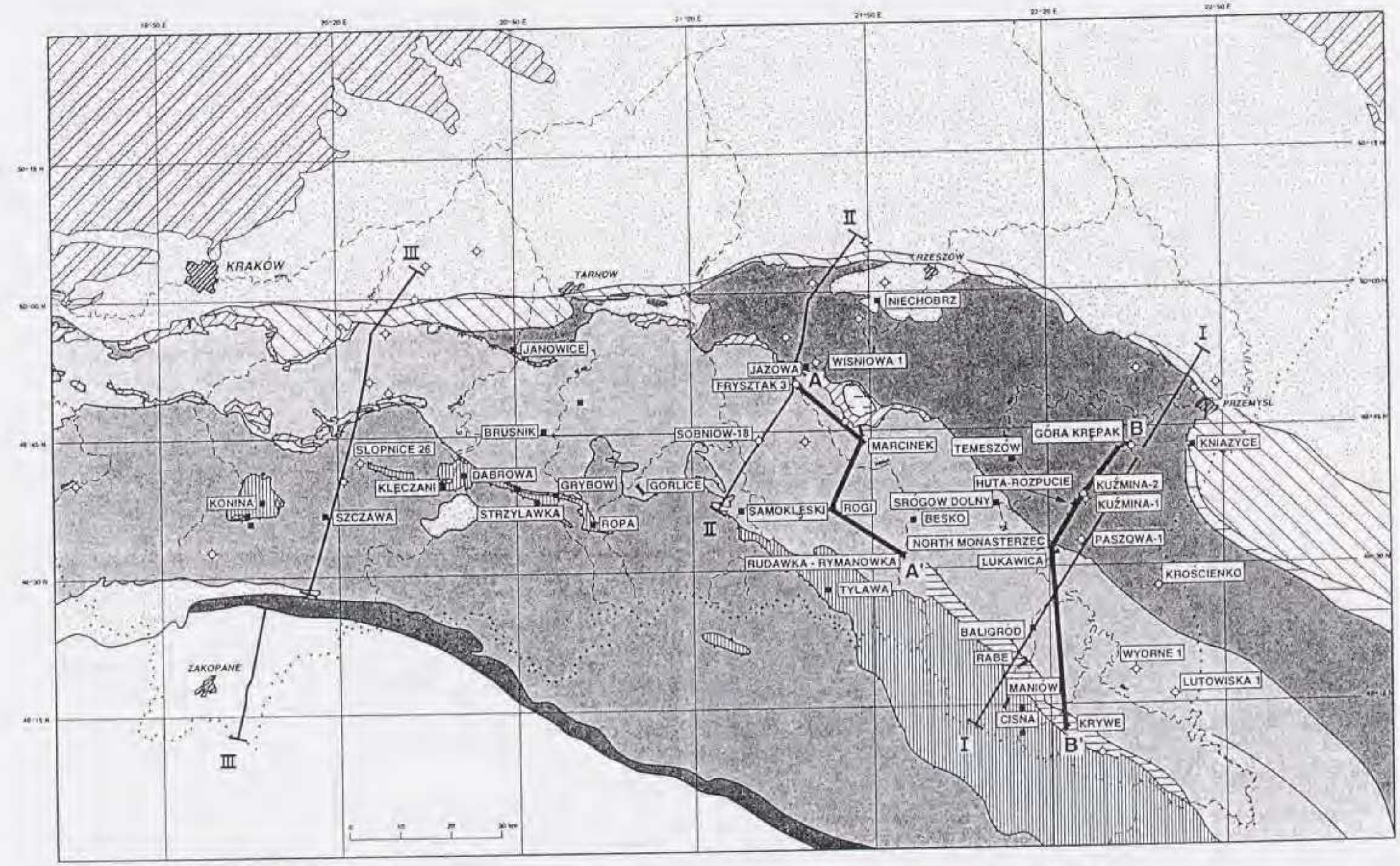

FIG. 7. Lacation map of Menilite and Krosno formations samples (wells and outcrops) and cross-sections A-A' and B-B', give in Fig. 8, and regional sections, given in Encl. 2.

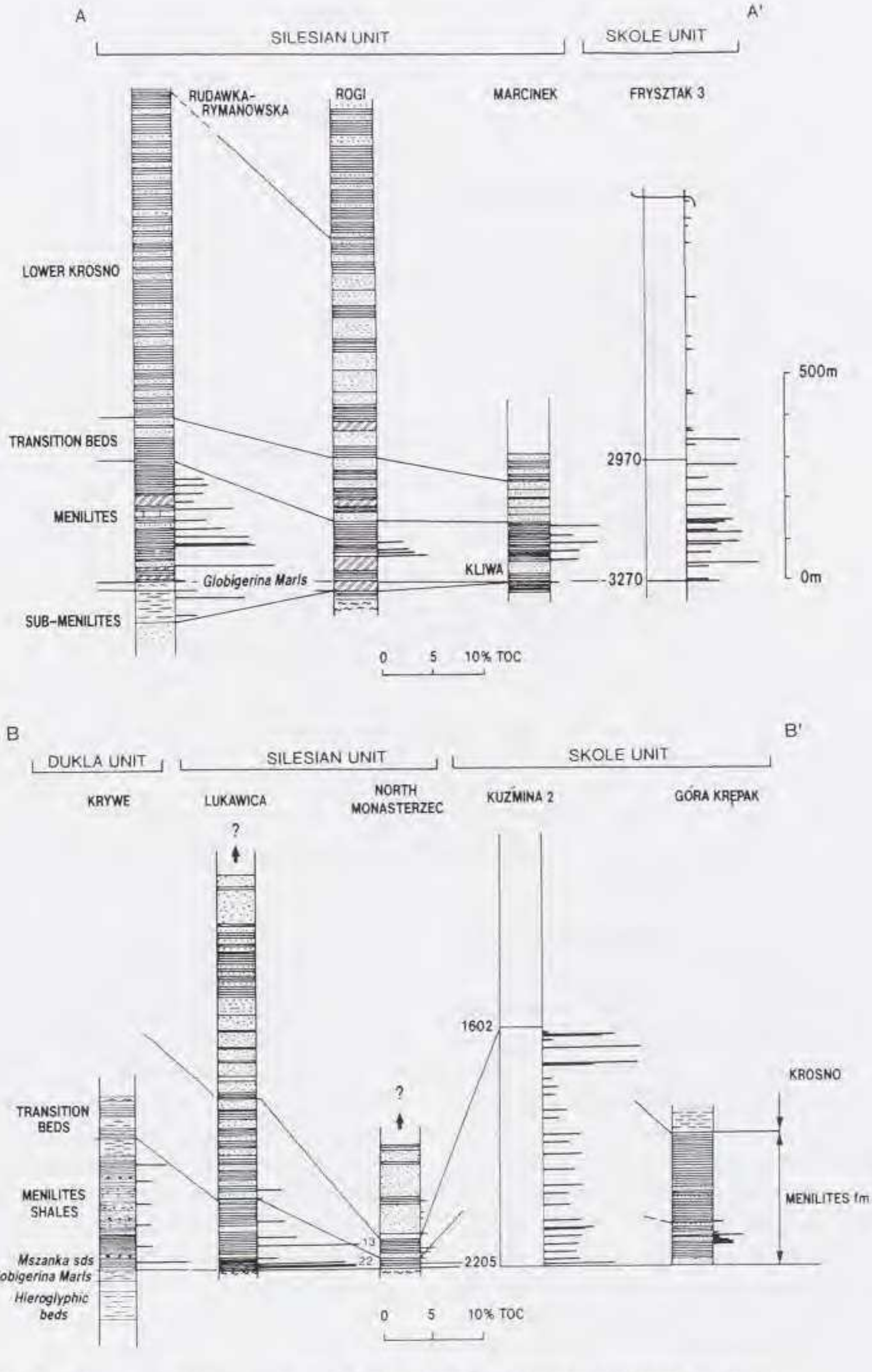

FIG. 8. Stratigraphic ross-sections A-A' and B-B', showing variations in thickness and TOC values of the Menilite shales (top of Globigerina marls has been taken as a horizontal marker).

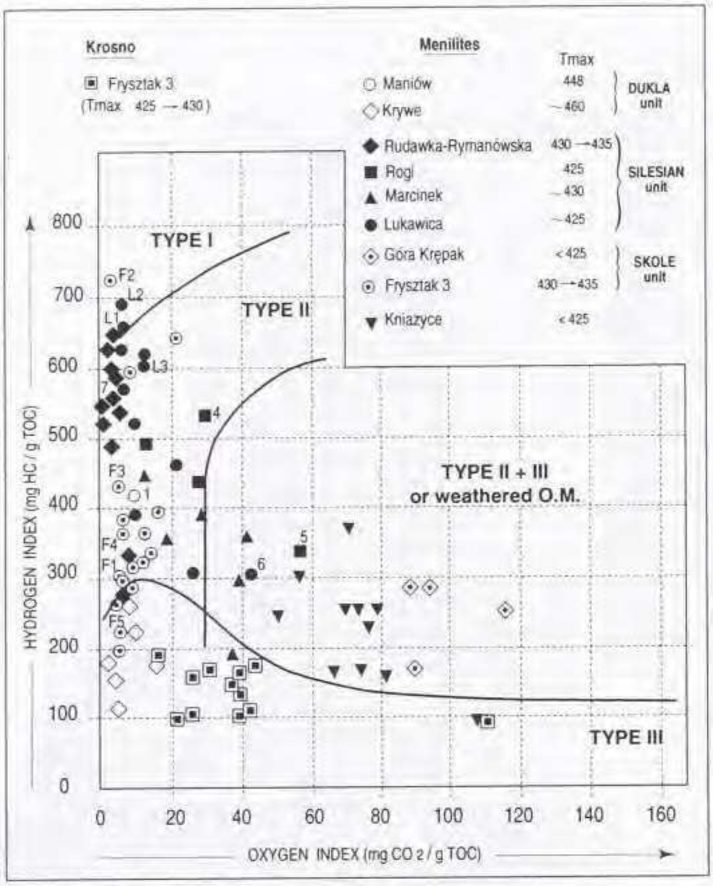

FIG. 9. Hydrogen Index-Oxygen Index diagram for Menilite and Krosno formations

enhanced by restricted bottom water circulation due to a complex sea-floor topography involving basins and cordilleras. The complex vertical as well as lateral variations in terrestrial input may be related to the interference of such factors as the emergence of cordilleras supplying terrigenous material to the adjacent sub-basins, and gravitational mass flow processes which locally can strongly modify the organic facies as seen, for example, in lake Tanganyika (Huc, 1988). In this respect, the eastern part of the Skole basin differs from the other sub-basins in so far as terrestrial influx from the platform commenced already at the beginning of the Oligocene.

In conclusion, the Menilite formation contains the best potential source-rocks. However, the observed substancial lateral and vertical variations in organic content and quality require high density data for a reliable evaluation of the petroleum potential of the Carpathians. Several Early Cretaceous shales also represent potential, though less prolific, source-rocks; these are the Spas shales in the Skole basin and the upper Cieszyn formation in the Silesian basin and Fore-Dukla unit. In the Dukla basin and equivalent units of the western Carpathians, the occurrence of Cretaceous source-rocks has not yet been demonstrated but is possible. Lastly, Carboniferous shales and coals may be considered as potential souce-rocks; however, such a statement has to be confirmed by additional investigations.

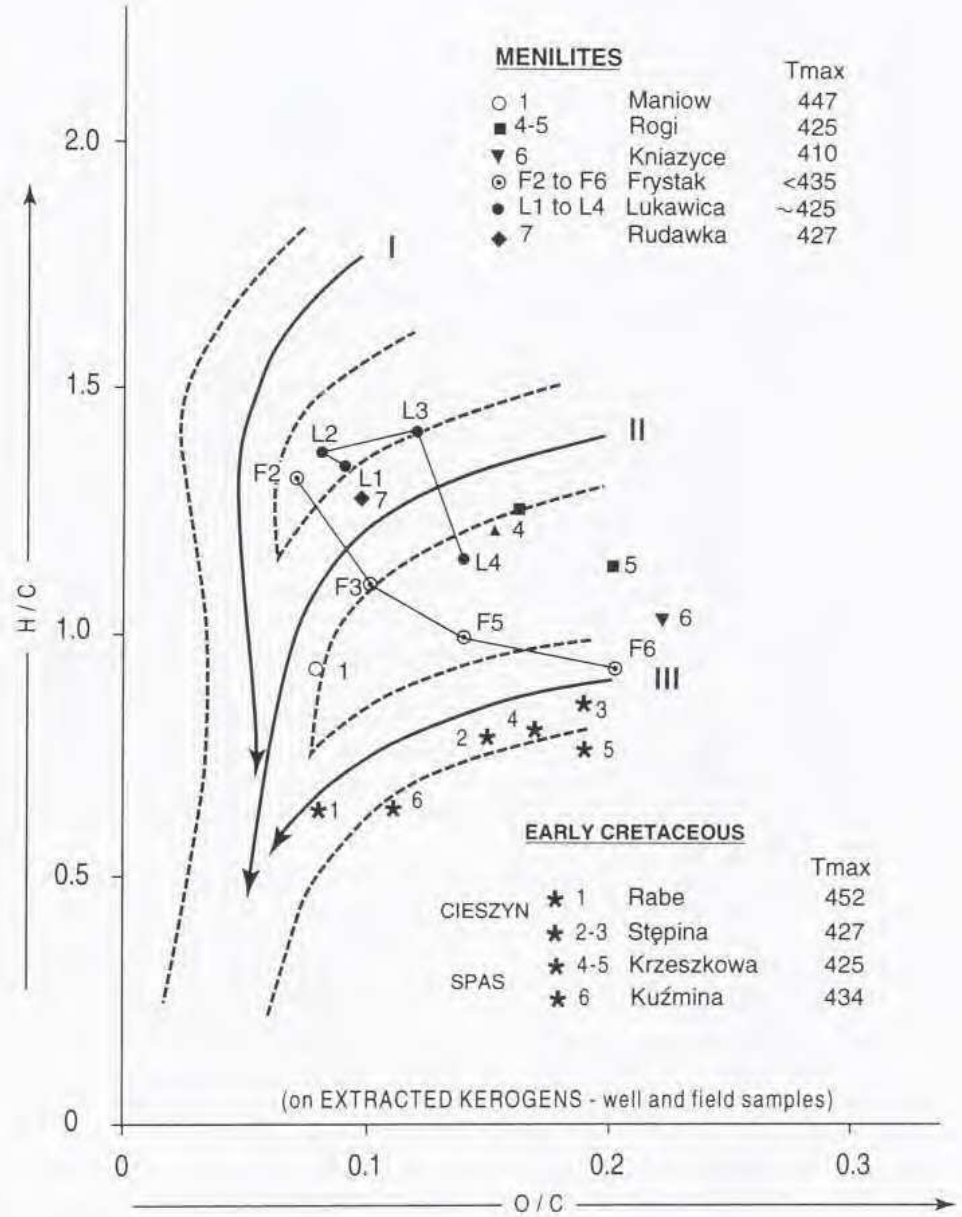

FIG. 10. Van Krevelen diagram for Early Cretaceous and Menilite samples.

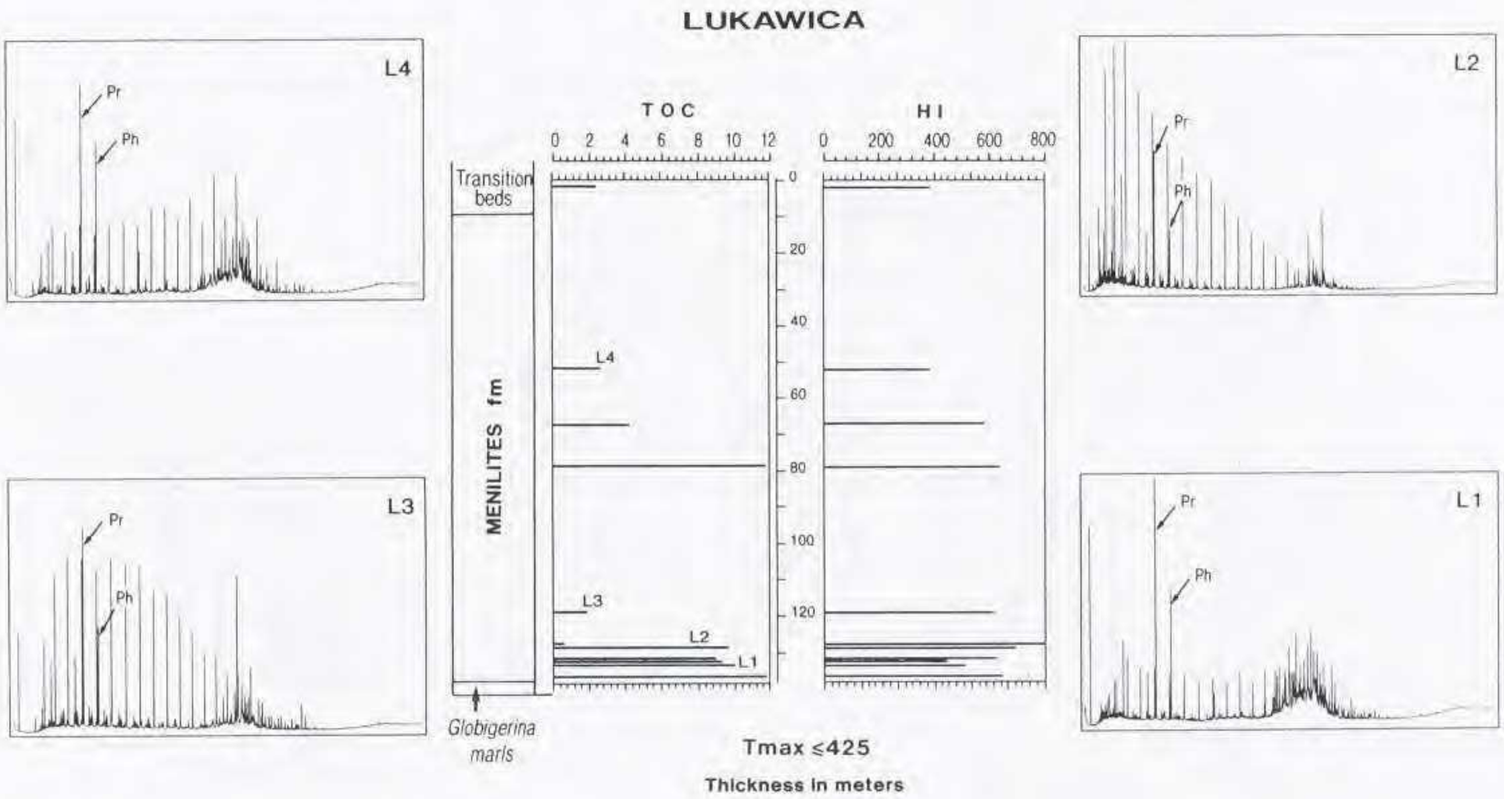

FIG. 11. Main geochemical results at Lukawica site.

PETROLEUM OCCURRENCES AND SOURCE-ROCK CORRELATIONS

Petroleum Occurrence

In the autochthon (Encl. 3), more than 70 gas fields produce from Miocene reservoirs. These fields are mostly located in the eastern, wider and deeper part of the Carpathian foredeep in the subsurface prolongation of Holy Cross Mountains, the so-called Upper San River High, where Neogene sediments directly rest on a Precambrian substratum. In the western Carpathian foredeep, a few gas fields also produce from Miocene reservoirs beneath the Outer Carpathian thrust. The gas contained in these accumulations has been demonstrated to be biogenic in origin (Kotarba, 1987, 1992). The occurrence of thermogenic gas is restricted to few Triassic, Late Jurassic and Late Cretaceous reservoirs (Kotarba and Jawor, 1993).

In addition, about 10 fields produce oil from Late Cretaceous sandstones and Late Jurassic carbonates. These are located west of the Upper San River High. Few oil accumulations have been discovered in Palaeozoic strata which are preserved in blocks adjacent to this structure on its southwestern (Early Carboniferous and Late Devonian reservoirs) and its northeastern flank (Ordovician-Silurian reservoirs).

In the allochthon (Encl. 3), more than 80 oil fields and a few gas fields, all of relatively small size, have been found in Cretaceous to Oligocene reservoirs. Most of them are located within the Silesian unit and produce mainly from (Cretaceous)-Paleocene Istebna sandstones and/or Eocene Ciezkowice sansdstones (Fig. 2). In the southeastern part of the Silesian unit, oil comes from Oligocene Krosno sandstones. In the Skole unit, only about ten fields, all but one located at its southern edge, produce oil from Oligocene Kliwa sandstones (Encl. 1). In addition, some accumulations are located in the Magura unit (Cretaceous-Paleocene Inoceramus beds), the Dukla and equivalents, and the Sub-Silesian unit (Cretaceous Weglowka marls and sands). All gas accumulations are sourced by thermogenic gas (Kotarba, 1987).

Geochemical Analyses of Oil And Source-Rock Extracts

From the 90 or so oil accumulations occurring in the different plays of the Carpathian foredeep and the Outer Carpathians, 65 representative oil samples were collected and analysed (Ten Haven et al., 1993). In addition, 12 source-rock samples were selected from the general geochemical screening and their extracts were analysed by Gas Chromatography-Mass Spectrometry (Ten Haven et al., 1993) to be compared to oil samples.

Geochemical analyses of oil samples from reservoirs of different ages permit the distinction of two oil families, the global composition of which (saturated hydrocarbons between 50% and 70% and less than 20% of NSOs) indicates an overall similarity (Ten Haven et al., 1993).

The first oil family, represented by only one sample (Nosowka; Encl. 3), has an isotopically light signature, abundant C29 steranes, and lacks, in contrast to the second family, characteristic biomarkers such as the oleanane.

The second oil family comprises all other oil samples from the foredeep as well the allochthon (Encl. 3), between which no significant differences could be observed (Ten Haven et al., 1993). This family has an isotopically heavier signature and is characterized by the presence of oleanane and 28,30-*dinor*-hopane, in some oils the highly branched C25 isoprenoïd alkane (HBI) and in one sample several additional biomarkers characteristic of terrigenous input.

The presence or absence of oleanane is of key importance for determining the origin of oils because this biomarker can be used both as a facies and as a stratigraphic marker. As it is an Angiosperm-derived marker, its occurrence implies a land-plant contribution to the respective organic matter. On the other hand, as Angiosperms appeared during the Early Cretaceous and proliferated during the Late Cretaceous and Tertiary (Moldowan et al., 1993), the presence of oleanane implies than the respective source-rocks must be Cretaceous or younger. However, its absence does not necessarily speak for a pre-Cretaceous source-rock because this can also be linked to an organic matter of purely marine origin. The origin of the two other main biomarkers is unknown: the 28,30-

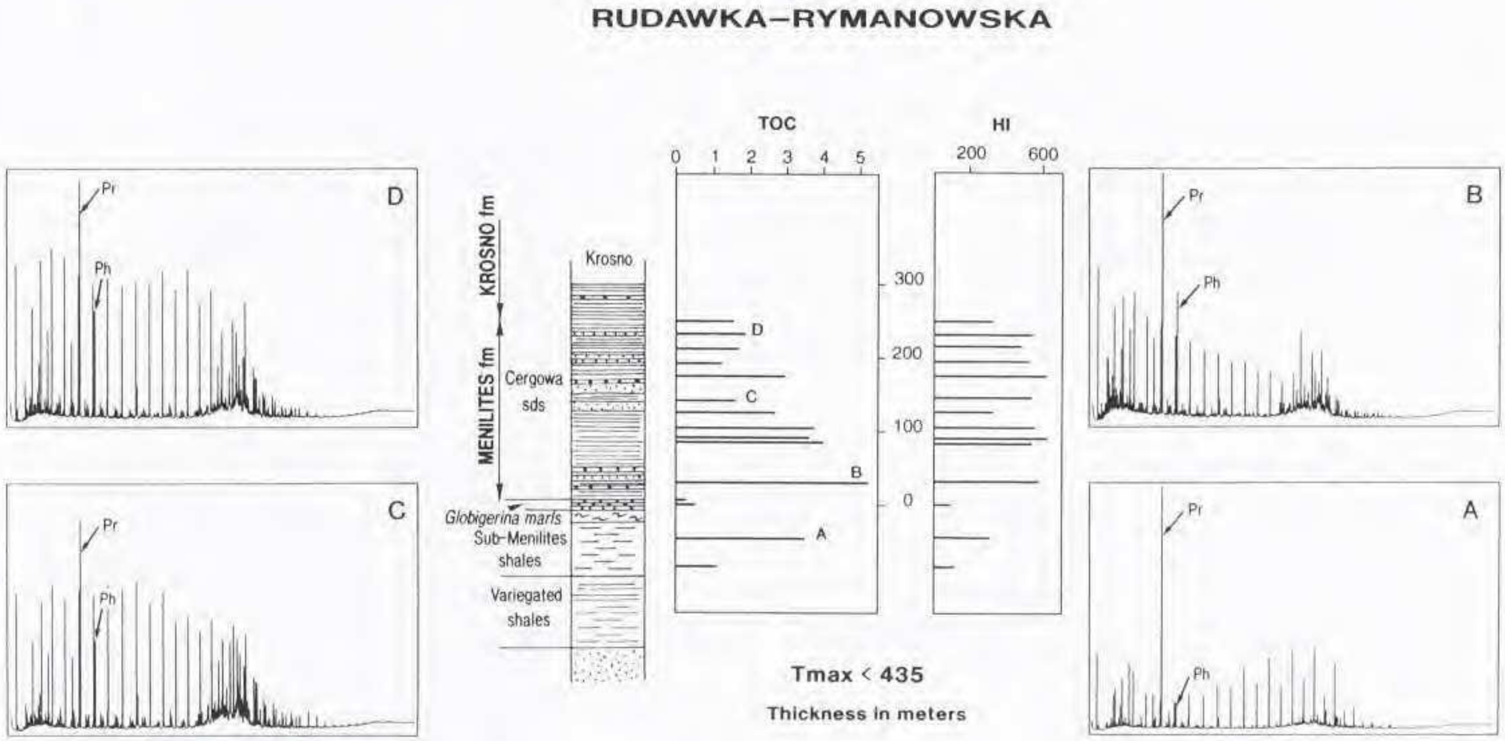

FIG. 12. Main geochemical results at Rudawka-Rymanowska site.

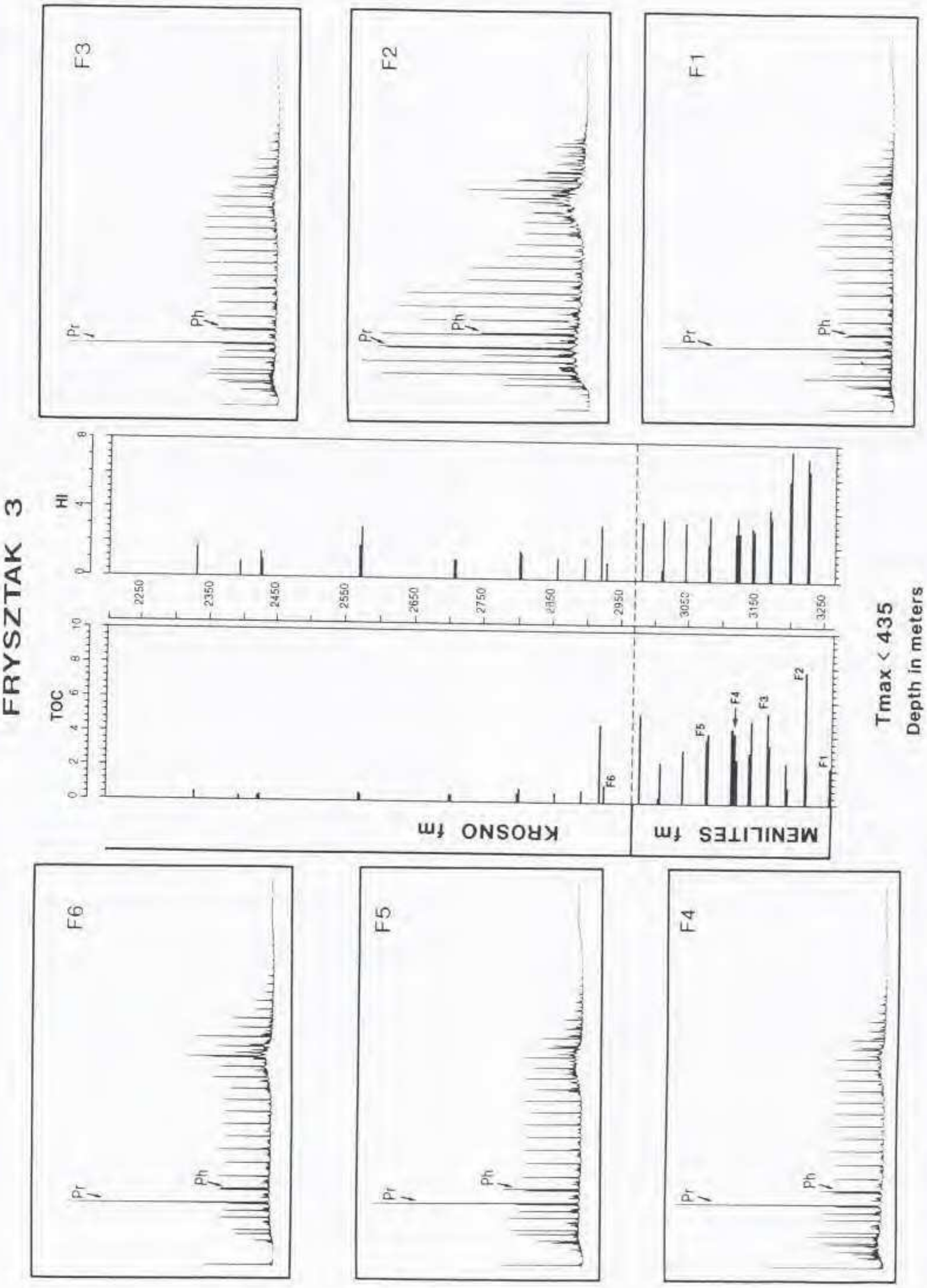

FIG. 13. Main geochemical results of Frysztak 3 well.

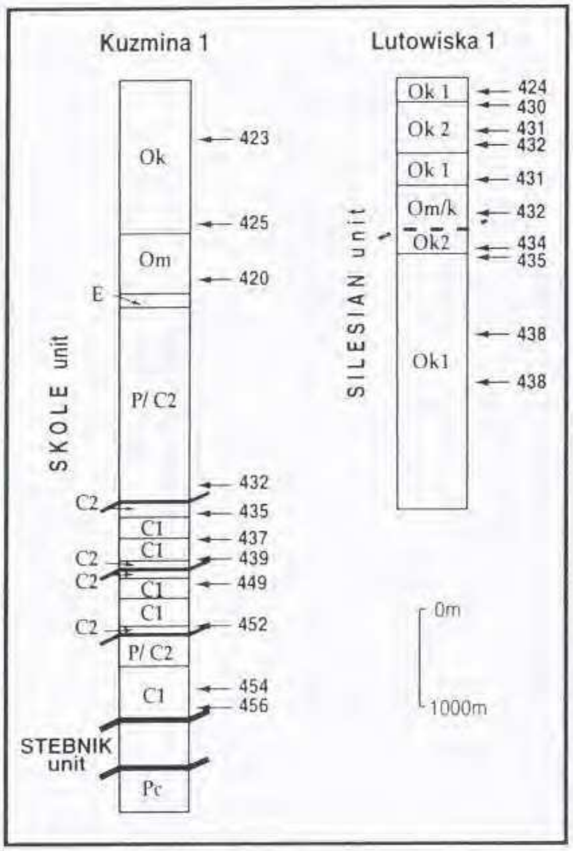

FIG. 14. Two examples of post-compressional maturation trends, based on Tmax from Rock Eval analyses.
Legend : 423 : Tmax. O : Oligocene; k : Krosno; k2 : middle Krosno; k1 : lower Krosno; m/k : intermediate beds; m : Menilites; E : Eocene; P : Paleocene; C2 : upper Cretaceous; C1 : lower Cretaceous; Pc : Precambrian.

dinor-hopane might be of bacterial origin, the HBI could be sourced by diatoms (Ten Haven et al., 1993). However, these markers are considered as useful tools for oil/oil and oil/source-rock correlations.

Based on sulphur contents and relative abundance of these biomarkers, the second family can be grouped into the following sub-sets (Encl. 3):

Group A is characterized by the dominance of higher-plant derived triterpanes and is represented by only one oil, located on the central northern margin of the Silesian unit.

Group B is characterized by abundant 28,30-*dinor*-hopane and comprises the oils reservoired in Kliwa sandstones of the Skole unit.

Group C lacks these specific characteristics and embraces all other oils found in reservoirs of the different allochthonous tectonic units.

Group D also lacks these specific characteristics but differs by a high sulfur content. It includes all samples from the foredeep, except Nosowka.

Hydrocarbon extracts from source-rocks were made on 3 Early Cretaceous samples (Cieszyn, Spas formations), 9 samples from Menilite shales covering the range of different compositions and organic contents, and 2 samples from Carboniferous series.

The analysis by GC-MS showed that all the Menilite samples contain oleanane, except in Lukawica L2; the absence of oleanane in this sample is very likely related to its pure marine origin, well documented by Rock-Eval, elemental and GC analyses (Fig. 11). The other biological markers (HBI, 28,30-*dinor*-hopane) were also found but with strong abundance variations. One sample (Kniazyce -see location on Fig. 7) contains numerous additional biomarkers of terrigenous origin. These variations within the Menilite shales confirm variations in terrestrial input ranging from a "pure" land-plant organic matter (Kniazyce) to a "pure" marine organic matter (L2) with all the intermediate compositions.

In contrast, Early Cretaceous samples contain neither oleanane nor any other of the above mentioned compounds. No other specific biomarker has been identified which could permit to unequivocally give an Early Cretaceous source for a crude-oil.

The Early Carboniferous black-shale and Late Carboniferous coal samples gave typical biological marker fingerprinting which significantly differ from each other.

Oil/Source-Rock Correlations

The characteristics of the first oil family (Nosowka oil) exclude a Late Cretaceous-Tertiary source-rock and suggest a **Paleozoic source-rock.** Moreover, they also appear atypical for oils derived from an Ordovician shale or a Devonian carbonate source-rock. The fingerprints of the Nosowka oil and of the Late Carboniferous coal sample exhibit certain similarity, suggesting a possible correlation. However, this conclusion remains speculative as it is based on a single sample only, and definitely requires additional investigations.

The presence of oleanane in all oils of the second family indicates that the **Menilite shales** are the source-rock for these oils. However, a correlation of the different groups with one particular lithofacies of the Menilites remains questionable as oils obviously have an average composition and are derived from a wide spectrum of organic facies recorded within this formation. The oil of group A might be tentatively correlated with Menilite shales having a content in terrestrial organic matter (Kniazyce and possibly Frysztak upper Menilite samples). The oils of groups B and of C, the more frequent ones, could be derived from an intermediate facies, characterized by a mixture of marine and terrestrial organic matter. Such an assumption is reasonable, considering the vertical and lateral variations in organic facies at a basin scale. The geographically restricted occurrence of group B oils is striking, but no satisfactory explanation can be given for it.

The group D oils from the foredeep have been clearly generated and expelled from Menilite shales. Although not supported by the maturity data, the high sulfur content of these oils suggests an earlier stage of generation and expulsion as compared to the other oils of this family (Ten Haven et al., 1993).

Mixing of oils derived from Menilite shales with oils generated from other source-rocks might be possible, even if it cannot be proven to-date. It is speculated that, within the Outer Carpathian overthrust, the Early Cretaceous source-rocks might have contributed to the presently pooled oils, particularly in the southeastern part of the Silesian basin (Cieszyn formation) and in the Skole basin (Spas formation); in Grobla field, a contribution from a Carboniferous source-rock cannot be excluded.

EVOLUTION OF PETROLEUM SYSTEMS

Present and Inherited States of Maturation

The present-day state of source-rock maturation has been investigated using Rock-Eval maturation index (Tmax) from outcrop and core samples. In particular, data from deep boreholes (Kuzmina 1-2, Paszowa 1) and/or wells penetrating complex tectonic structures (Frysztak 3, Lutowiska 1) provided useful insight. In this way, data of Lutowiska 1 or Kuzmina 1 wells (Fig. 14) clearly evidence that the present-day maturity trend is the result of a post-thrusting evolution: in Kuzmina 1, Tmax regularly increases from 435 to 455 within a succession of three stacked recumbent folds, involving normal and overturned early-Late Cretaceous series (Fig. 15).

Assuming this feature as representative for the entire Outer Carpathians, maturity levels have been drawn along the eastern and central cross sections (Fig. 15). Some conclusions can be reached by analysing these cross sections and by considering additional scattered maturity data in the western zone. However, these conclusions must be regarded only as a first approach of the present state of maturity in Outer Carpathian owing to the tectonic complexity of the area and the lack of sufficient maturity data.

The Menilite formation is immature in the whole Skole unit, except in Frysztak area where the Menilites are buried underneath the Silesian and the Sub-Silesian thrusts. In contrast, the Early Cretaceous Spas shales might be in the oil window in the southern part of this unit.

No maturity data is available in the Silesian unit of the western Outer Carpathians. Elsewhere, Menilite shales could be mature in the southeastern part of this unit and within some deep synclines to the northwest. Early Cretaceous source-rocks could be mature in most thrust sheets of this unit.

The Grybow, Fore-Dukla, Dukla and equivalent western units exhibit all a high level of maturity. The maturity stage in the Magura unit cannot be evaluated for lack of data.

The autochthonous Miocene source-rock is immature to slightly mature (T_{max}<440) over the sampled depth range, from 400 to 3300 m.

Problem Of Inherited States Of Maturation

The present-day maturity of the source-rocks is the result of a complex thermal history which involves a first pre-compression episode, during which sedimentary overburden provides for source-rock burial and maturation, and a second post-compression episode during which their burial is only caused by tectonic emplacement of thrust sheets. Actually, large parts of the Skole and possibly also the Silesian units did not undergo tectonic burial and their sedimentary sections were only eroded since thrust emplacement. In contrast, tectonic overburden was important in more internal units. Furthermore, this process was more important in the western parts of the Carpathians where the Magura nappe was largely thrusted onto both the Grybow and Obidowa-Slopnice nappes, than in the eastern parts where this nappe was probably thinner and its thrusting onto the Dukla unit more restricted. An another case of tectonic overburden is the Fore-Dukla triangle zone (cross section I, Fig. 16) where a high and reversed maturity trend has been observed in the outcropping section (Tmax decreasing in older formations). This feature is reliably accounted for by the Neogene emplacement of several duplexes invoked for this structure (Roure et al., 1993; Roca et al., 1995); therefore, the present-day maturity trend has been acquired lately. In these examples, the tectonic overburden severely overprinted the pre-compression source-rock maturity stage.

Actually, modelling is required to integrate all parameters controlling hydrocarbon generation in an effort to separate between pre- and post-thrusting maturation levels. However, some reasonable approximations can be made for areas which have been only eroded since thrust emplacement. Owing to erosion, source-rocks underwent decreasing temperatures, even assuming a constant heat flow. The period of time taken into consideration is short (about 15 Ma) and the impact of this factor on maturation has been demonstrated to be neglegible. Consequently, the source-rock the maturation level remained constant since thrust emplacement. Therefore, the present Tmax, as measured in outcrops, reflects the pre-thrusting maturation pattern.

This qualitative approach leads us to consider that in the Skole basin, neither the Early Cretaceous series nor the Menilite shales have entered the oil-window prior to thrust deformation. In the Silesian basin, Early Cretaceous strata were located within the oil-window and the Menilite shales might have entered it, at least in the deepest parts of the basin.

Possible Migration Trends

Hydrocarbon migration models for Outer Polish Carpathians must account for the following facts:

(1) Oils found in the autochthonous Mesozoic platform reservoirs were sourced from the Oligocene Menilite shales. This implies long distance migration from an oil kitchen located in the presently allochthonous units. Oil charge from the Skole basin, although located adjacent to the platform, can be excluded because the Menilite shales are immature in this basin. Therefore, hydrocarbons must come from more internal units.

(2) The Paleogene basin was dissected by cordilleras which were repeatedly reactivated, particularly during middle-late Oligocene times.

(3) In the autochthon, the Cretaceous and most Jurassic reservoirs are sealed by the shaly and evaporitic basal series of the Badenian Molasse. Therefore, effective oil entrapment could not occur before the middle Miocene.

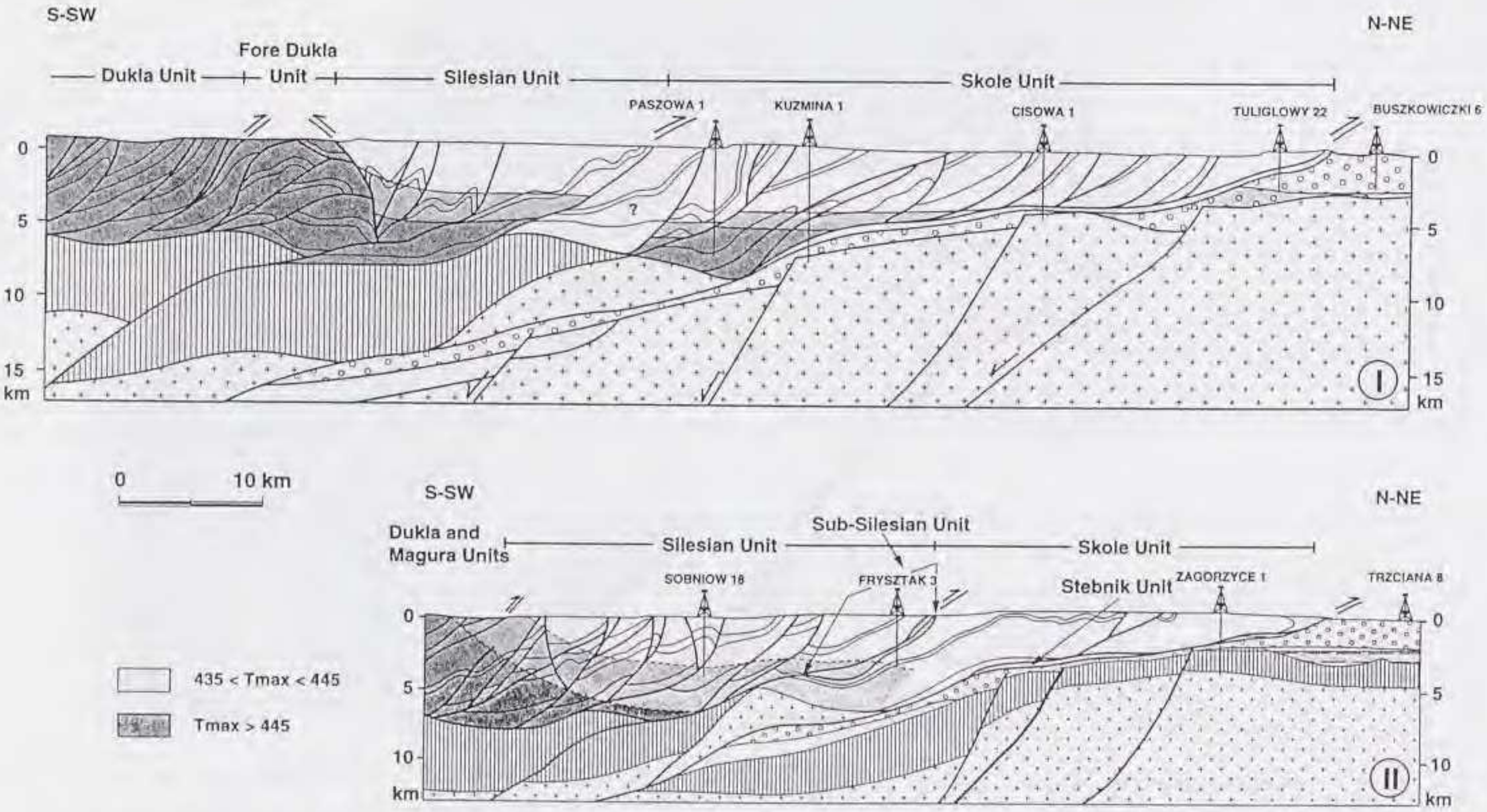

FIG. 15. Tentative reconstruction of the present-day states of maturity along the eastern (I) and central (II) cross-sections -with two maturation levels : Tmax = 435 i.e. beginning of the oil-window for type II and III, Tmax = 445 i.e. intra oil-window (Espitalié et al., 1985).

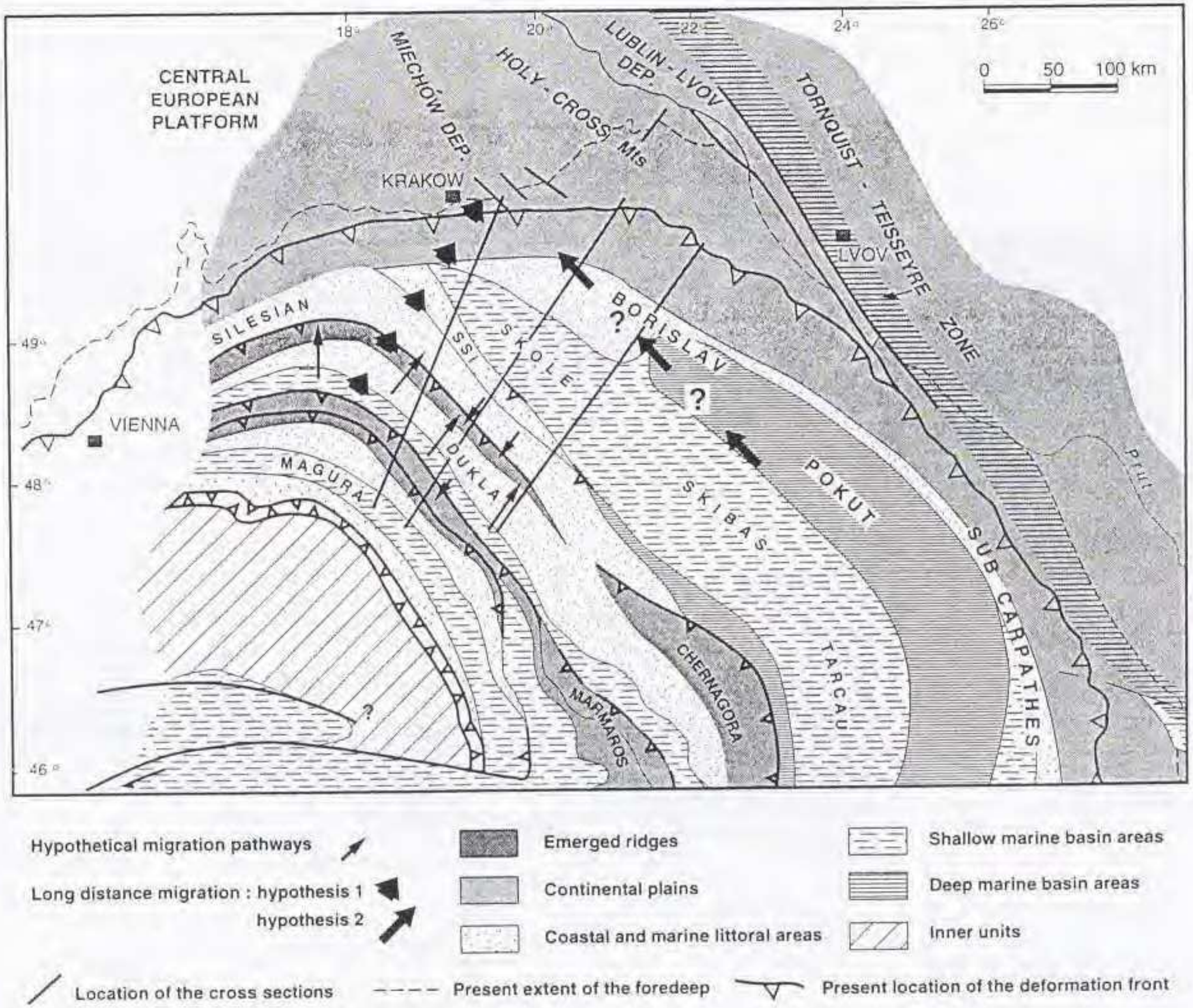

FIG. 16. Hypothetical migration trends before the main phase of thrusting (palinspastic restoration at late Oligocene - simplified from Ellouz and Roca, 1994).

Integration of these different constraints implies an accurate knowledge of the geometry and kinematics of the tectonic units versus the maturation state kinetics at the different stages of the structural history of the basin. Particularly questionable is the whether long distance migration, charging platform reservoirs, has indeed taken place. The presence of cordilleras prior to the main deformational phase and the generally complex geometry of the entire Carpathians, favour a short distance migration hypotheses. Actually, this question would require forward modelling to explore intermediate and pre-deformation geometries. Modelling would also be useful to precisely define the maturation state of the different source-rocks, to evaluate their respective contribution and to locate mature areas prior to thrust deformation. Thus, the scenario proposed below is only a preliminary attempt which will have to be confirmed or modified, once adequate modelling is available.

In this scenario, we assume an early generation of oil, prior to the Neogene deformation of the Carpathians, from Early Cretaceous source-rocks in the Silesian basin and possibly in Dukla basin, as well as from Menilite shales in the deep parts of the Dukla and Silesian basins. Oil probably started to migrate towards the palaeo-highs of internal units of the Outer Carpathians before their Neogene deformations (Fig. 16). However, volumes of oil were probably limited and restricted to the Fore-Dukla sub-unit which would have been charged from the adjacent Silesian and Dukla basins. Only Early Cretaceous oil might have migrated towards the Sub-Silesian unit. These early oil accumulations were subsequently restructured and destroyed by remigration and/or overmaturation.

At the end of the Oligocene, emplacement of the Magura nappe strongly increased maturity of the Menilite shales, particularly in the Obidowa-Slopnice unit in western areas, resulting in possibly important oil expulsion and migration. At this time, the Obidowa-Slopnice unit was not yet folded. Moreover, emplacement of the Magura nappe increased flexural subsidence of the whole area, thus favouring regional updip long distance migration towards the Mesozoic platform from the Obidowa-Slopnice unit (Fig. 16) (note that migration from the Dukla basin is not realistic as this basin was only slightly overridden by the Magura nappe and was separated from the platform by the wide Skole basin). However, the Mesozoic reservoirs in the foreland were at this time not yet sealed. A possible scenario is entrapment of oils in intermediate structures, the closure of which was reduced during the subsequent continued flexural subsidence of the basin, causing the release of oil towards the platform. However, another hypothesis could be a much younger structuration. Actually, this apparent inconsistency between an assumed late Oligocene age of deformation and oil expulsion, and a Badenian age for trapping, could result from errors in dating the onset of the deformation. As a matter of fact, reworked faunas are frequent in flysch sequences; therefore, their age can easily be overestimated. Assuming a younger age for the deformation of the entire Outer Carpathians (no older than Badenian, even for the Magura thrust emplacement) would provide a simple solution for both tectonics and petroleum migration. Whatever the hypothesis, this scenario is in agreement with the geochemical analyses which suggest a slightly earlier time of generation and expulsion for the oils of the foredeep than for the oils trapped in the allochthonous reservoirs.

During and after thrusting, short distance migration occurred in each separate tectonic unit, from its deeper parts towards the adjacent highs. This scenario appears to apply for the Dukla and equivalents and the Silesian basins. Remigration from the Silesian unit very likely accounts for accumulations in the Sub-Silesian unit. In contrast, accumulations within the Skole unit can only be explained by remigration from the Silesian unit and/or by a contribution from Cretaceous source-rocks contained in the southernmost part of the Sklole basin. This peculiar situation might account for the existence of the distinct group B oil in this basin. In contrast, no specific oil group can be ascribed to the other units; C-group oil is present in all units and no conclusion can be drawn from a single A-type sample, the location of which might be rather due to facies variation of the Menilite shales.

SUMMARY AND CONCLUSIONS

Extensive geochemical surveys carried out in the Polish Outer Carpathians confirm that the Oligocene Menilite shales are the primary source-rocks, that they are characterized by strong lateral and vertical heterogeneities and vary from a very good type II to a mixed type II+III. In addition, some Early Cretaceous shales appear to play the role of secondary potential source-rocks; however, their contribution to oils accumulated has not been clearly established.

The Menilite shales have been identified as the main source for all the oils trapped in the overthrust as well as most of the oils, except one, trapped in the foredeep. This correlation is supported mainly by the common presence of oleanane in these oils. Minor biomarker differences observed must be partly related to changes in organic facies of the Menilite shales.

There are indications for two distinct episodes of oil generation : 1) an early generation phase occurred prior to and at the very beginning of compressional deformation due to deep sedimentary burial of the Menilite shales in Dukla and Silesian basins; 2) a late generation phase occurred after thrust emplacement of the allochthounous units due to tectonic burial of the source-rocks.

Available data suggest that most of the oil accumulations in the allochthon may be charged by oils generated during the post-thrusting stage. On the other hand, the source area and the timing of the oil charge of traps occurring in the foredeep remain debatable. The preferred working-hypothesis envisages a combination of early long distance migration from the northwestern internal Outer Carpathian units, oil accumulating in intermediate structures and their subsequent destruction during the main orogenic phases, causing updip migration of oils into the foreland. Detailed basin modelling is required to determine whether this hypothesis is valid. An alternate hypothesis invokes lateral long distance migration from the most internal parts of the Borislav-Pokut basin (Fig. 16). Such migration could be facilitated by sandstone intercalations in the Menilite shales along the northeastern margin of this basin. This would imply a marked northwestward component in the flexural subsidence of the incipient Carpathian foreland basin for which we have, at this time, no evidence.

For the Ukraine, relatively short distance migration can be invoked for the oils trapped in Mesozoic reservoirs of Lopushnia field, located in the autochthon just in front of the Borislav-Pokut nappe (see Izotova and Popadyuk, Sovchik and Vul, this volume). A Menilite origin has been clearly established for this oil (Lafargue et al., 1994; Ellouz et al, in preparation). Reconstruction of pre-thrusting geometries permits to consider migration along the flexural trend from the more internal parts of the Borislav-Pokut and possibly the Skiba basins where Menilite shales were already mature. Comparison of the geological settings of the Ukrainian and Polish Carpathians at the end of the Oligocene, shows major differences between the two areas (Fig. 16). In Ukraine, oil kitchens are located rather close to the foreland and are not separated from the latter by cordilleras. Therefore, the scenario developed for the Ukraine cannot be directly applied to Poland. Thus, the petroleum system of the Polish Outer Carpathians may be unique in the entire Carpathians fold-and-thrust belt.

Several points require further clarification:

(1) Have Early Cretaceous potential source-rocks indeed and substantially contributed to the hydrocarbon habitat of the Carpathians as suggested here for the Skole unit?

(2) Do Carboniferous coals and/or shales represent an additional source for oils occurring in autochthonous reservoirs?

(3) Do Late Jurassic basinal shales and carbonates of the autochthon represent an alternate source, as evident in the Vienna basin of Austria (Ladwein et al., 1991)? In the Polish and Ukrainian Carpathian foreland, Late Jurassic neritic carbonates grade laterally into pelagic carbonates and shales (Izotova and Popadyuk, this volume). If these series has source-rocks characteristics and if it is preserved beneath the Skole unit of Poland, it may have contributed to its hydrocarbon habitat. However, the present deep burial of Jurassic sediments (Encl. 2) suggests that they are post-

mature for oil generation and thus, may yield gas only.

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Enclosures

Encl. 1 Tectonic map of the Polish Outer Carpathians (after Zytko et al., 1989; Sokolowski, 1954; Widzinski, 1950-1954), showing distribution of oil and gas fields (modified after Petroconsultant, 1994) and location of the cross-sections given in Encl. 2.

Encl. 2 Geological cross-sections through the Polish Carpathians (for location see Encl. 1) Section I and II: modified after Roure et al. (1994), section III: modified after Roca et al. (1995)

Encl. 3 Stratigraphy and structural location of oil and gas reservoirs in the autochthon and allochthon. For explanations see text. Stratigraphy of the autochthonous reservoirs: N1-Miocene, Cr2-Late Cretaceous, J3-Late Jurassic, J2-Early Jurassic, T-Early Triassic, C1-Early Carboniferous, D-Devonian, S-Silurian, O-Ordovician, Cm-Cambrian.
Stratigraphy of the allochthonous reservoirs: Ok-Oligocene Krosno beds, Okl-Oligocvene Kliwa sds, Ocr-Oligocene Cergowa sds, Omg-Oligocene Magdalena sds, Eh-Eocene Hieroglyphic beds, Ec-Eocene Ciezkowice sds, Pis-Paleocene Istebna beds, Pin-Paleocene Inoceramus sds, Cr-Pin-Paleocene-Cretaceous Istebna sds, Cwm-Late Cretaceous Weglowka marls, Cws-Early Cretaceous Weglowka sds.